# THE CHALK RIVER SUPERCONDUCTING HEAVY ION CYCLOTRON

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## Abstract

A superconducting heavy ion cyclotron has been chosen as the accelerator to extend the range of the Chalk River MP tandem. The tandem-cyclotron combination will accelerate all ions from Li (to 50 MeV/nucleon) through U (to 10 MeV/nucleon). The design of the integrated accelerator facility is underway as well as a full scale modelling program for both the magnet and RF system - the current status of these programs is reported.

## 1. Introduction

The Chalk River superconducting heavy-ion cyclotron is intended to extend the capability of our existing MP tandem accelerator. It was chosen from several competing post-tandem accelerator concepts because of its relatively modest cost, the successful operation of coils using twisted multifilament NbTi superconductor and the high quality beams available from small precision cyclotrons. Since the original proposal[1)] the design has evolved[2,3)] to the concept described below. Nevertheless, the original estimated cost of 2.2 million 1973 dollars for the accelerator remains unchanged. Table I lists the beam parameters from the tandem-cyclotron combination and Fig. 1 compares the accelerator's maximum specific energy as a function of mass with several existing and proposed accelerators.

Table I

Cyclotron Parameters

| | | |
|---|---|---|
| Energy range | U | 3-10 MeV/u |
| | C | 6-50 MeV/u |
| Current | C | 200 pnA |
| | Cu | 50 pnA |
| | U | 4 pnA |
| Emittance | | $2\pi$ mm mrad |
| Energy resolution | | 4 : $10^4$ |

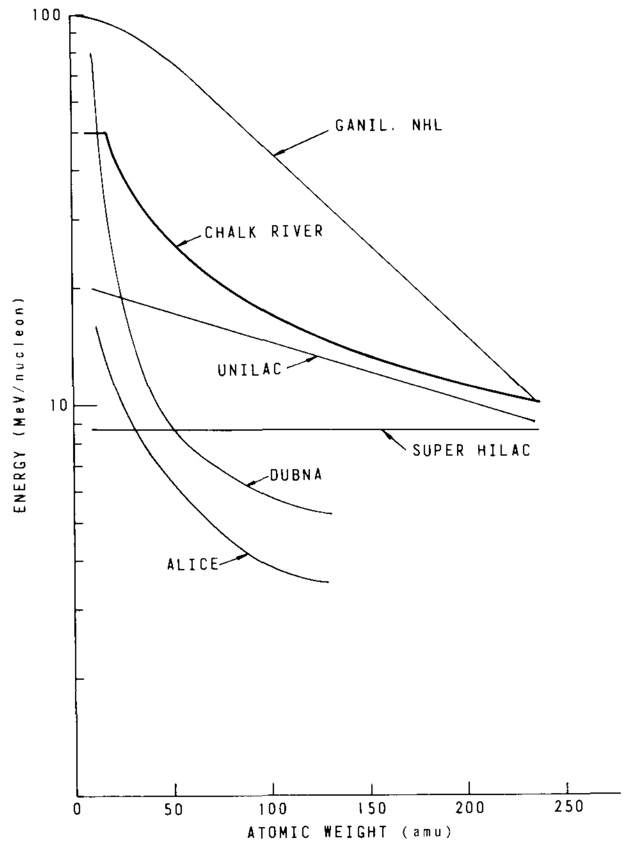


Fig. 1. Comparison of maximum specific energies of some heavy-ion accelerators (existing and proposed).

The cyclotron magnet is excited by a pair of 3 x $10^6$ ampere-turn superconducting coils that give a maximum average field of 5 T. Field flutter is provided by four magnetically saturated iron hills. Ions from the tandem are bunched and chopped, then injected along a trajectory in the midplane of the cyclotron. When the beam is tangent to the innermost orbit in the cyclotron it is intercepted by a carbon foil, stripped to a higher charge state, then accelerated to the extraction radius of 650 mm by a four-dee resonator system. The outer-turn separation is enhanced by the integral radial resonance and a

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conventional electrostatic deflector deflects the beam into a superconducting magnetic channel that compensates for the defocusing magnetic gradient along the escape trajectory. A conventional system then transports the beam to the experimental area.

We are building a full-scale model of the magnet and radio-frequency accelerating structure to ensure that we can meet the stringent stability requirements listed in the parameter tables. Most of the components in this model should be directly transferable to a final accelerator. Concurrent with this modelling program we are proceeding with the design of the complete facility.

## 2. Description

As much as possible of the d.c. beam normally produced by the tandem Van de Graaff[4] must be compressed into $3^{\circ}$ RF phase buckets prior to stripping at the centre of the cyclotron. These short bunches are essential to achieve the desired energy resolution from the cyclotron. Attaining them is no trivial feat because the bunching is hindered by ion source energy spread and tandem transit time jitter. Calculations have been made for a system using a second-harmonic double-drift buncher between the ion source and the tandem, a second buncher immediately after the tandem and a chopper preceding the cyclotron; these calculations have shown that more than 25% of the tandem output beam can be bunched into the required $3^{\circ}$ within an acceptable energy spread.

If all incoming ion trajectories originate at a fixed point at the outside edge of the cryostat, then the stripping foil can be located at a fixed azimuth (in the centre of a dee) and need only move radially from a minimum radius of 150 mm to a maximum of 220 mm to accommodate all ion species. A steering magnet to deflect the beam through a maximum angle of $\pm 3\frac{1}{2}^{\circ}$ is sufficient to direct the trajectories of all ion species to the correct interception point with the carbon foil (see insert Fig. 2).

A typical beam cross section at the stripper foil is 2 mm radially x 8 mm axially. This size best uses the available aperture taking into consideration the calculated betatron frequencies, the measured emittance ($1.4\pi$ mm mrad for 70 MeV Cl) from

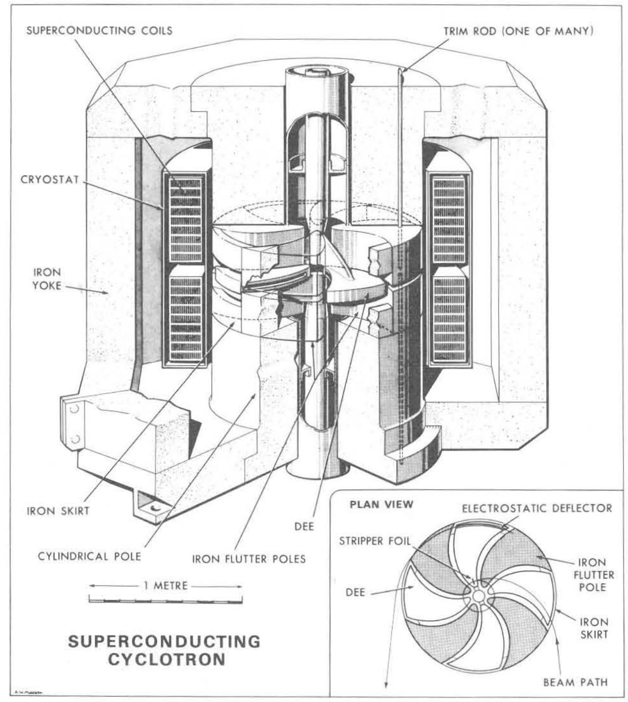


Fig. 2. Current concept of superconducting cyclotron.

the tandem[5] and the calculated phase space deterioration from small angle scattering in the foil[6]. For this beam cross section and the currents listed in Table I, a foil lifetime of several hours is projected from measurements with iodine beams[7].

The accelerating system consists of four "dees" supported by the center conductors of two shorted coaxial lines concentric with the magnet. The top line supports a pair of dees $180^{\circ}$ apart and the bottom line supports a similar pair of dees at $90^{\circ}$ to the first pair (see Fig. 2). This structure forms a pair of coupled resonators with two modes whose frequencies are varied by adjusting the position of the shorts. In 0-mode the top and bottom resonators oscillate in phase, and in $\pi$-mode, in antiphase. Operation with harmonic numbers 6, 4 and 2 is proposed for specific energy ranges 3 - 5.6, 5.6 - 21, and 21 - 50 MeV/nucleon respectively in $\pi$, 0 and $\pi$ modes. The peak voltage of 100 kV across the eight accelerating gaps and the high ion charge state give a large energy gain/turn e.g. greater than 25 MeV per orbit for $U^{33+}$. Figure 3 is a photograph of the 1/10 scale model used to verify the adequacy of the tuning range. The model is shown split at the midplane. Table II lists the RF parameters.

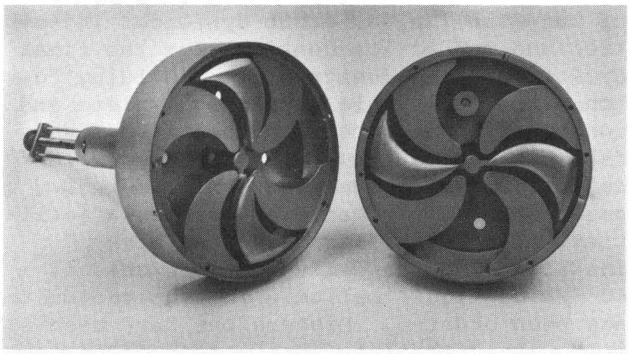

Fig. 3. 1/10-scale model of radio-frequency structure used to verify that the tuning range is adequate.

Table II

RF Parameters

| | |
|---|---|
| Frequency range | 31-62 MHz |
| Voltage stability | 1 : $10^4$ |
| Frequency stability | 1 : $10^6$ |
| Power | ~ 100 kW |

The required average mid-plane magnetic field varies from 1.5 to 5 T. It is generated by a pair of multifilament NbTi superconducting coils (maximum excitation = 6 mega-ampere-turns) inside an octagonal iron yoke as shown in Fig. 2. The coils are wound from a 17 mm x 4 mm copper strip with a 4 mm x 2 mm soldered insert of 54 0.25 mm diameter Nb-48% Ti filaments in a copper matrix. The filaments within the insert are twisted with a pitch of 50 mm to reduce the duration of flux jumping instabilities to an acceptably short time. Full cryostatic stabilization is ensured by the overall 25:1 copper-to-superconductor ratio and the large area of copper in the pancake windings exposed to liquid helium. Table III lists other pertinent coil parameters.

The coils are immersed in separate 4.5 K helium baths suspended in a common cryostat vacuum tank. The calculated thermal load is ~ 25 W and is distributed roughly equally amongst the transfer tube, current leads and radial bracing. The helium refrigeration plant has a capacity in excess of 100 W at 4.5 K.

The yoke and pole configuration shown in Fig. 2 is both a magnetic and radiation shield and reduces the required ampere turns. Access to the cyclotron midplane is achieved by removing either the top or bottom pole-piece assemblies - each is mounted on a permanent jacking system.

Table III

Superconducting Coil Parameters

| | |
|---|---|
| Inside diameter | 1500 mm |
| Outside diameter | 1900 mm |
| Height | 650 mm |
| Separation | 120 mm |
| Number of pancake windings/coil | 32 |
| Number of turns/pancake | 42 |
| Conductor weight | 9280 kg |
| Maximum operating current | 2300 A |
| Magnet inductance | 10.6 H |
| Maximum stored energy | 28 MJ |
| Maximum hoop stress | 60 MPa |
| Field stability | 1 : $10^5$ |

Field flutter from four spiralled magnetically saturated iron hills provides axial focusing. Iron skirts partially fill the valleys near the extraction radius; they decrease the flutter but are essential for isochronizing the field. The iron hills are saturated over the entire operating range, hence the flutter varies inversely as the square of the mean magnetic field[2,8]. This increases the upper energy limit (imposed by axial focusing) as the required magnetic rigidity decreases, giving rise to the shape of the "Chalk River" curve in Fig. 1. Figure 4 shows $\nu_z$ as a function of radius for 10 MeV/nucleon uranium and 50 MeV/nucleon carbon.

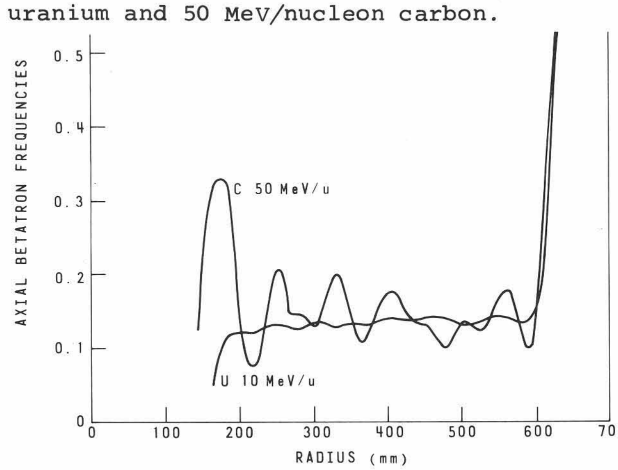


Fig. 4. Axial betatron frequencies for 50 MeV/nucleon carbon and 10 MeV/nucleon uranium. The ripple in the carbon curve is caused by the trim rods. This ripple will be reduced when the azimuthal positioning of the rods is optimized.

In addition to the wide range in average magnetic field, the required radial magnetic profile varies from essentially flat to the extreme case of a 5% increase near the extraction radius. To accomplish this, the main coils are split into an inner and outer pair relative to the mid-plane and coarse trimming is achieved by changing their relative excitation. Fine tuning of the radial profile is accomplished with trim rods[9] - iron cylinders that extend from the top and bottom of the yoke to the midplane surface of the hills. By retracting the rods, the local magnet gap is increased and the local field decreased. Adequate field trimming is available from rods at twelve radial positions (96 rods in all), the inner five positions with rods of 40 mm diameter, the outer seven positions with rods of 60 mm diameter. In addition to trimming the radial profile the rods can be used to correct field harmonics.

Table IV

Yoke Parameters

| | |
|---|---|
| Overall height | 3020 mm |
| Outside dimension - flat to flat | 3360 mm |
| Wall thickness | 500 mm |
| Pole diameter | 1380 mm |
| Hill gap | 40 mm |
| Valley gap | 640 mm |
| Weight | 170 Mg |
| Maximum attractive force | 10 MN |

The turn separation of the outside orbits, already large because of the high energy gain per turn, is enhanced by the integral radial resonance, permitting the beam to clear the septum of an electrostatic deflector located within a dee. This deflector generates a maximum radial electric field of 130 kV/cm and subtends an azimuth of $\sim 30^{\circ}$. A magnetic channel follows to reduce the local magnetic field and to counteract the steep gradient in the field fall-off region which otherwise causes strong radial defocusing. Several configurations of $Nb_3Sn$ superconducting coils are being considered to generate the channel fields. A conventional system transports the beam to the experimental area.

## 3. Current Status

We are building a full-scale model of the magnet and radio-frequency accelerating system while proceeding with the design of the complete facility. Calculations sufficient to specify the model parameters have been made; detailed computer studies of magnetic fields, orbit dynamics, injection and extraction continue for the final cyclotron. The design of the building to house the full scale model is complete and construction is scheduled to start this fall; an adjacent building has been allocated for superconducting coil winding, small scale experiments and support facilities. The helium liquefier has been installed and has delivered in excess of 40 $\ell$/h of liquid helium. The superconductor has been ordered. Discussions have been held with potential fabricators of the iron yoke and final quotes are due in early September. Fabrication of the full scale RF system is scheduled to start this fall and a 20 kW, 30-60 MHz supply has been installed for preliminary tests.

The first stage of our program, which includes initial measurements on the full scale models of the RF accelerating structure and magnet, is expected to be sufficiently advanced by mid-1977 so that technical feasibility is established and preliminary cost estimates confirmed. If satisfactory results are obtained we hope to then proceed with conversion of the model to a working accelerator.

## References


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DISCUSSION

J.H. ORMROD: Could you comment on the interesting concept of trim rods. How are they actuated and how reproducible should they be?

J.H. ORMROD: The trim rods are moved by stepping motors. They must be positioned with an accuracy somewhat better than 0.1 mm.

F. RESMINI: Could you comment on what you mean by acceptable lifetimes of stripping foils?

J.H. ORMROD: From an extrapolation of 70 MeV iodine results we expect foil lifetime, depending on the ion, energy and current, from one hour to many hours.

F. RESMINI: When will your magnet go into standard operation?

J.H. ORMROD: We only have authorization for the model studies. If we get early authorization for conversion of the model to a working accelerator, we hope for operation in 1980.

J.A. MARTIN: You showed the foil stripper located at fixed azimuth. Does this arrangement require that the beam be injected over large range of azimuths.

J.H. ORMROD: The beam originates at a fixed point outside the cryostat. One must pay for this convenience by a small reduction in extracted current.

M. REISER: As to the iron rods for trimming the field, do they not produce a spatial ripple which could get you into problems with undesirable values of the axial and radial betatron frequencies (I am thinking of the $\nu_r = 1$ resonance, for instance)?

J.H. ORMROD: The text has a figure showing plots of $\nu_z$ for 10 MeV/u uranium and 50 MeV/u carbon. $\nu_r$ does have ripple but does not pass through unity.

G. BURTON: Have you given any consideration to the use of a superconducting cyclotron for acceleration of light ions, e.g. p, d, $\alpha$, and $He^{2+}$?

J.H. ORMROD: No.